Finishing of Gears by Ausforming

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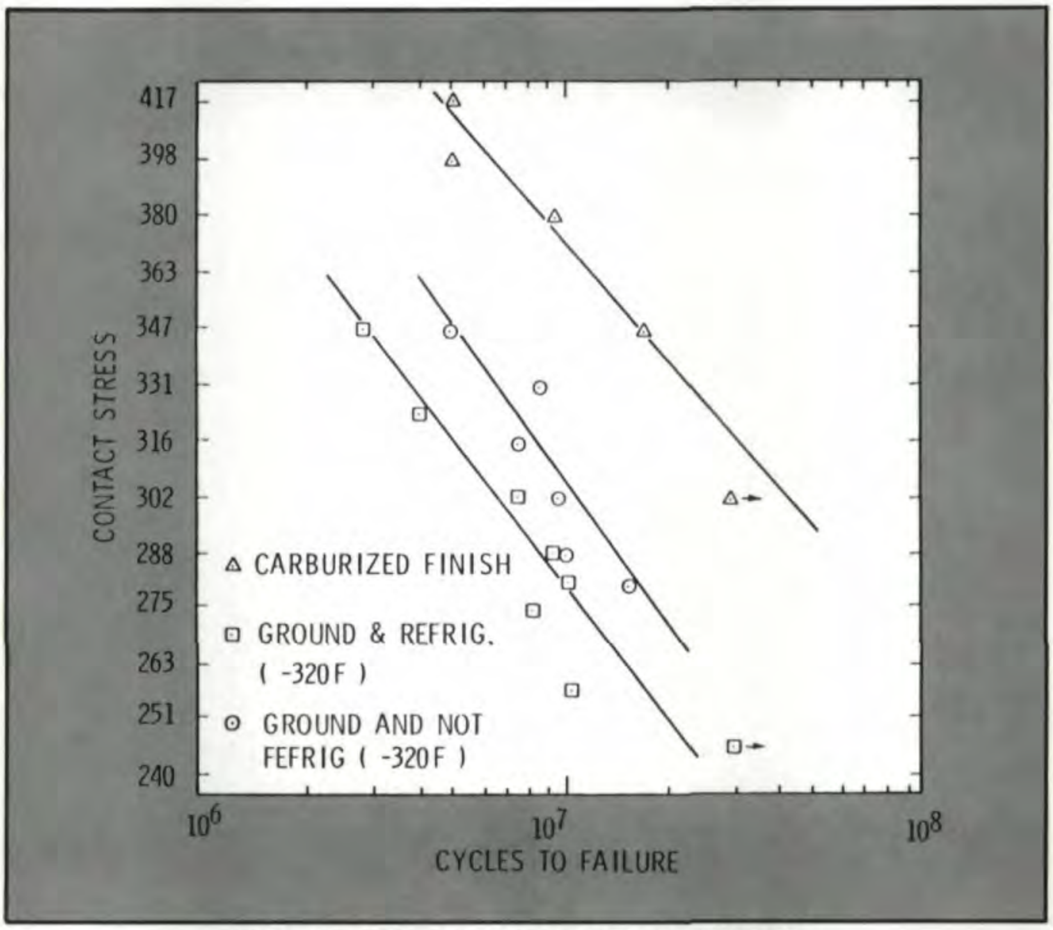

Fig. 1—Pitting fatigue of 9310 steel carburized to 0.90% carbon.

Abstract:

A low temperature thermomechanical finishing process now under development has the potential for producing longer gear life and stronger, more reliable and lower cost gears. This process ausforms the carburized surface of gear teeth while in the metastable austenitic condition during a gear rolling operation. A high degree of gear accuracy is possible by the combined use of interactive forming, low temperature processing and precision gear rolling dies. Thermomechanical processing can eliminate the need for hard gear grinding, thus offering substantial reductions in finishing costs as well as improvements in pitting fatigue life.

Introduction

Almost all machines or mechanical systems contain precision contact elements such as bearings, cams, gears, shafts, splines and rollers. These components have two important common requirements: first, they must possess sufficient mechanical properties, such as, high hardness, fatigue strength and wear resistance to maximize their performance and life; second, they must be finished to close dimensional tolerances to minimize noise, vibration and fatigue loading. As these requirements become more stringent, the cost of processing can increase significantly. The combination of mechanical properties and dimensional control is normally accomplished by separate manufacturing steps, each of which may partially nullify one or more of the desirable characteristics induced in the prior operation. For example, highly loaded precision gears are generally carburized to minimize plastic deformation and wear. They are then ground to achieve the necessary dimensional control, remove high temperature transformation products and improve surface finish. The optimum mechanical properties are developed in the as-carburized condition; thus, the finish grinding operation, which is required for achieving dimensional requirements, precludes achieving maximum strength and reliability. This point is illustrated by examining the pitting fatigue behavior of carburized 9310 steel subjected to various surface treatments.[1] (See Fig. 1.) The unground, as-carburized finish results in the best fatigue performance compared to the as-ground surfaces. Maximum dimensional stability and resistance to plastic deformation are achieved when the microstructure of the steel is totally martensitic. Diffusional transformation products, such as ferrite, lead to low hardness, as does untransformed austenite. The untransformed or "retained" austenite is also detrimental to dimensional stability, as it can eventually transform under mechanical stress to martensite, resulting in a volume change. Cryogenic treatments after normal quenching are often used to control the amount of retained austenite, as seen in Fig. 1. Such treatments can also have a detrimental effect on fatigue life.

Improvements in performance, reliability and manufacturing costs could be realized if surface finishing and strengthening were accomplished in a single process. Certain low temperature thermomechanical treatments, such as ausforming, have this potential. Ausforming treatment is applied to the steel while it is in the metastable austenitic condition prior to quenching to martensite. The principal benefit of this treatment is that it can produce significant improvements in strength without degrading toughness and ductility. In some steels, toughness is actually improved simultaneously with strength. The low temperature nature of this treatment produces very little thermal distortion, thus making it ideally suited for precision finishing operations. The ausforming process can be directly substituted for groups of conventional finishing processes, saving considerable cost while optimizing mechanical performance. Fig. 2 compares the processing steps for finishing gears by conventional methods with those required for ausforming. Ausform finishing can eliminate grinding, shaving, shot peening, honing and cryogenic treatments. The importance of eliminating grinding for optimized rolling contact fatigue life is illustrated in Fig. 3. Removal by grinding of more than 1 mil of surface material from 8620 steel carburized to 1.2C can severely reduce fatigue strength. This phenomenon can originate from two sources. First, the fatigue resistant compressive layers of carburized material are removed, and, second, incipient grinding damage in the form of microcracks and transformation products is generated.

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In addition to ausforming, other low temperature thermomechanical treatments for precision finishing are possible. Low temperature deformation during the decomposition of metastable austenite to bainite, known as isoforming, will result in significantly different toughness and strength characteristics than ausforming. Numerous other low temperature treatments are also possible, providing a large range of processing options and resulting effects.

Current Status of the Technology

The strengthening effect of ausforming is attributed to the inheritance of much of the dislocation structure and carbide

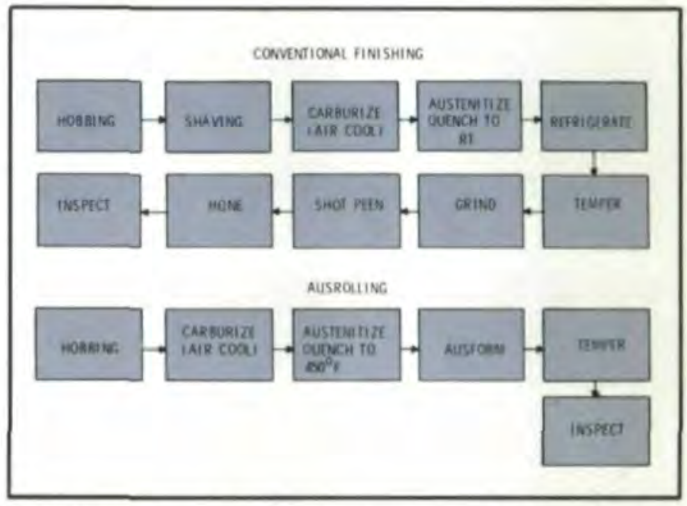

Fig. 2 – Comparison of manufacturing steps – conventional versus ausforming finishing of precision gears.

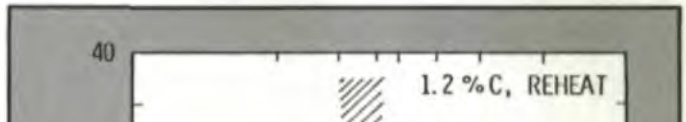

Fig. 3 – Fatigue life as a function of the amount of material removed. 8620 steel carburized to 1.2%C and reheat treated from 1550°F. All tests at 347 ksi.

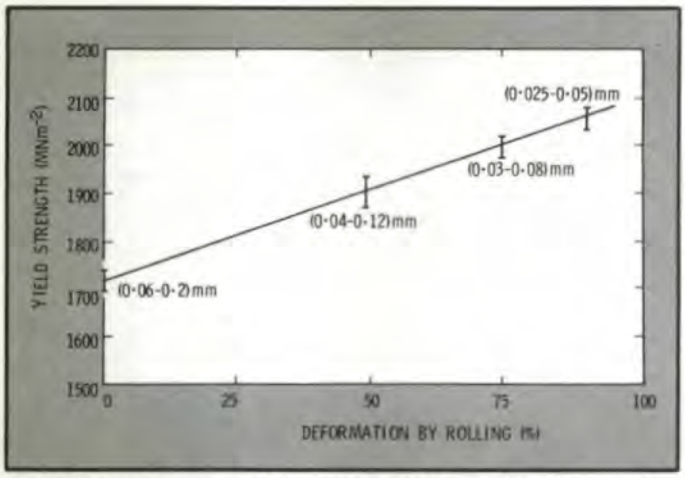

Fig. 4 – Effect of amount of deformation at 510°C on the yield strength of a 0.32C-3.0Cr-1.5Ni-1Si -0.5Mo steel. A range of martensite plate sizes (in brackets) was investigated at each deformation.[5]

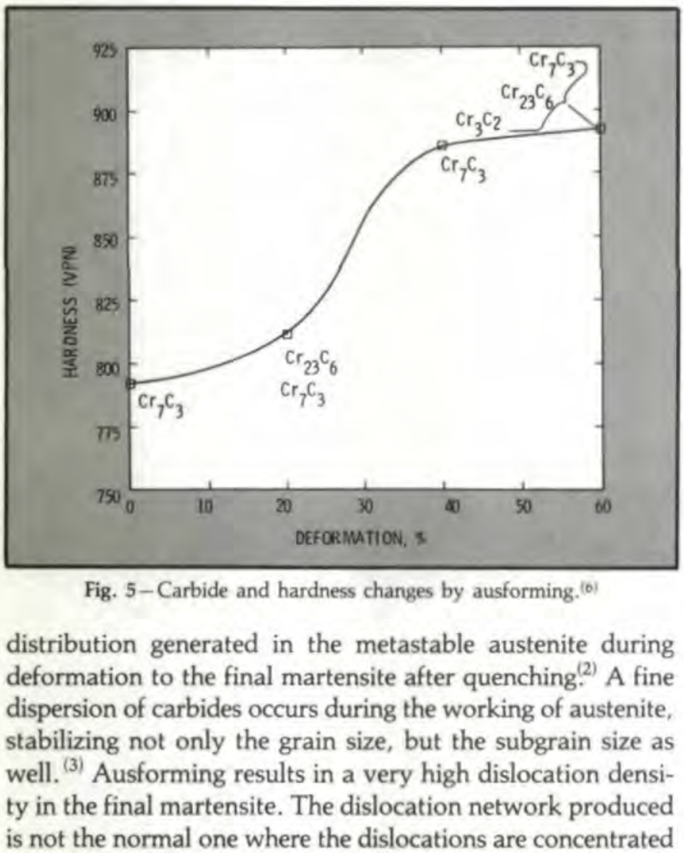

Fig. 5 – Carbide and hardness changes by ausforming.[6]

distribution generated in the metastable austenite during deformation to the final martensite after quenching.[2] A fine dispersion of carbides occurs during the working of austenite, stabilizing not only the grain size, but the subgrain size as well.[3] Ausforming results in a very high dislocation density in the final martensite. The dislocation network produced is not the normal one where the dislocations are concentrated at the cell walls; rather, they are more uniformly dispersed. Larger scale microstructure effects also play an important role in the strengthening process. The low working temperatures (in the range from room temperature to 1100°F, depending on alloy composition) tend to restrict austenite grain growth and, ultimately, the martensite plate size.[4-5] These effects combine to result in an increase in yield strength with increasing amounts of plastic deformation. The effect of the plastic deformation of metastable austenite on resulting martensitic plate size and strength for 0.32C-3.0Cr-1.5Ni-1.5Si-0.5Mo steel is shown in Fig. 4.[5] Each particular steel composition has a saturation limit above which very little further strengthening occurs. For a high-carbon, high-chromium cold-worked die steel (D2 tool steel), this saturation effect is

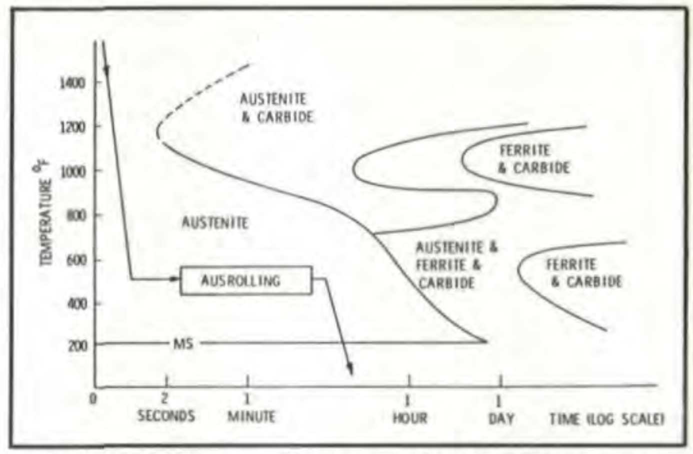

Fig. 6 – Schematic illustration depicting ausrolling time-temperature regime quench from austenitizing temperature.

associated with a change in carbide composition.[6] The change in hardness and carbide form over the range between 0 to 60% deformation is seen in Fig. 5.

The two principal requirements for a steel to respond effectively to the ausforming treatment are the presence of some carbide forming elements and the persistence of the austenite in the metastable form – that is, the existence of a deep austenite bay region in the isothermal time-temperature-transformation (T-T-T) curve – for a sufficient period of time to permit the required amount of deformation. Fig. 6 is the T-T-T curve for a 1.0C-1.2Cr-3.25Ni-0.13Mo steel (carburized 9310) exhibiting such a bay region. This steel has been successfully surface ausformed. Numerous highly alloyed steels are potentially ausformable; however, for low alloy steels, alloy modification or careful selection may be required. Some existing through-hardened steels that may prove to be satisfactory are 51B70, 4370 and 1580. There are also several low-alloy steels specifically developed for ausforming, one of which is the Si-Mn-Mo-V-Cu steel developed at RARDE over ten years ago.[7]

At the present time, it is not clear that thermomechanical forming near the martensite start temperature (M_s) is detrimental to the final properties. For conventional ausforming, working close to the M_s is not common practice since deformation can raise the effective martensite transformation temperature and promote the transformation reaction. In this case, a considerable volume of strong and brittle martensitic material would undergo deformation. If ausforming is confined to only the superficial layers, the formation of some martensite may be tolerated; and, indeed, may even be desirable.

Surface ausforming of carburized steel has been already demonstrated. Similar success may be possible for other surface conditions such as nitriding and carbonitriding. There is no experience available to suggest the effect of surface composition, case thickness or gradient on the properties of termomechanically treated surfaces.

Ausforming can have a significant impact on the tempering response of steel. These effects could be utilized advantageously to minimize processing operations and maximize mechanical properties. Two consequences of ausforming are the low carbon content and low degree of tetragonality of the subsequent martensite. These result from the precipita-

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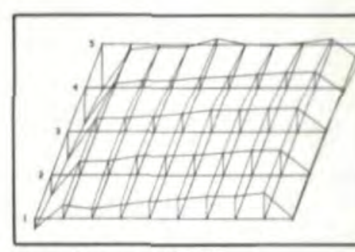
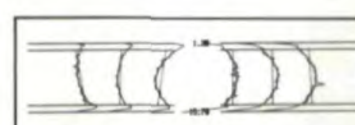


Bevel Gear Check



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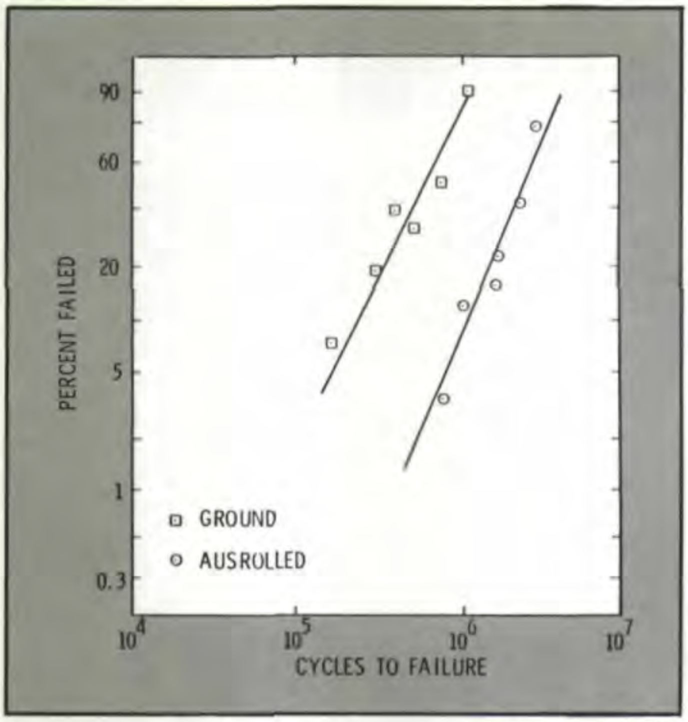

Fig. 7 – Rolling contact fatigue of EX15 steel at 450,000 psi contact stress.

tion of carbides during working. Ausforming steels of carbon contents above .3% can eliminate Stage I tempering, which would occur during the tempering of conventionally quenched martensite; thus, autotempering appears to be promoted by ausforming. For surface ausforming, optimum tempering treatments are most likely not those used for conventionally developed martensite.

At the present time, low temperature thermomechanical treatments have very few industrial applications. The reason is that substantial amounts of plastic deformation are required; thus, making it difficult to achieve uniform deformation in complex parts and requiring high forging presures and considerable energy expenditure. Applying low temperature thermomechanical treatments only to the surface of parts overcomes both of these limitations, rendering ausforming an ideal processing method for precision machine elements.

Ausforming significantly improves the rolling contact pitting fatigue strength of EX15 steel. Fig. 7 shows the Weibull distribution of rolling contact fatigue failures at a constant contact stress of 450 ksi for both ausformed and conventionally quenched and tempered steel. A significant improvement in fatigue life can be seen.

The principal features of the apparatus for precision ausforming of gears are interactive forming utilizing closed-loop control and a high accuracy forming die. A schematic diagram of this system is shown in Fig. 8. In this apparatus, the gear rolling die is driven by a hydraulic motor, and the workpiece gear is engaged and driven by the die. A special lead profile is generated on the die gear to produce a swagging action on the workpiece as it is being fed into the die. This geometry, illustrated in Fig. 9, shows a crown section on the bottom half of the lead and is used in the final finishing operation.

The control architecture allows for control signals for the vertical and horizontal feed to be either independent or dependent on each other. Command signals can be dynamically modified based on feedback signals from each of the four transducers. The current system is supervised through a 9600 baud serial link to the external microprocessor. The system is under actual position control at all times, but is in virtual load control during the deformation operation by use of the external microprocessor which supervises the generation of the command signal. The surface austenitization is accomplished with a 10 KHz AF induction system. Thermal monitoring is performed with a noncontacting fiber optic IR sensing pyrometer. This system is capable of measuring temperature over the range from 600 to 1800°F using a zinc sulfide detector. The system response time is one millisecond, permitting continuous reading of the temperature over gear

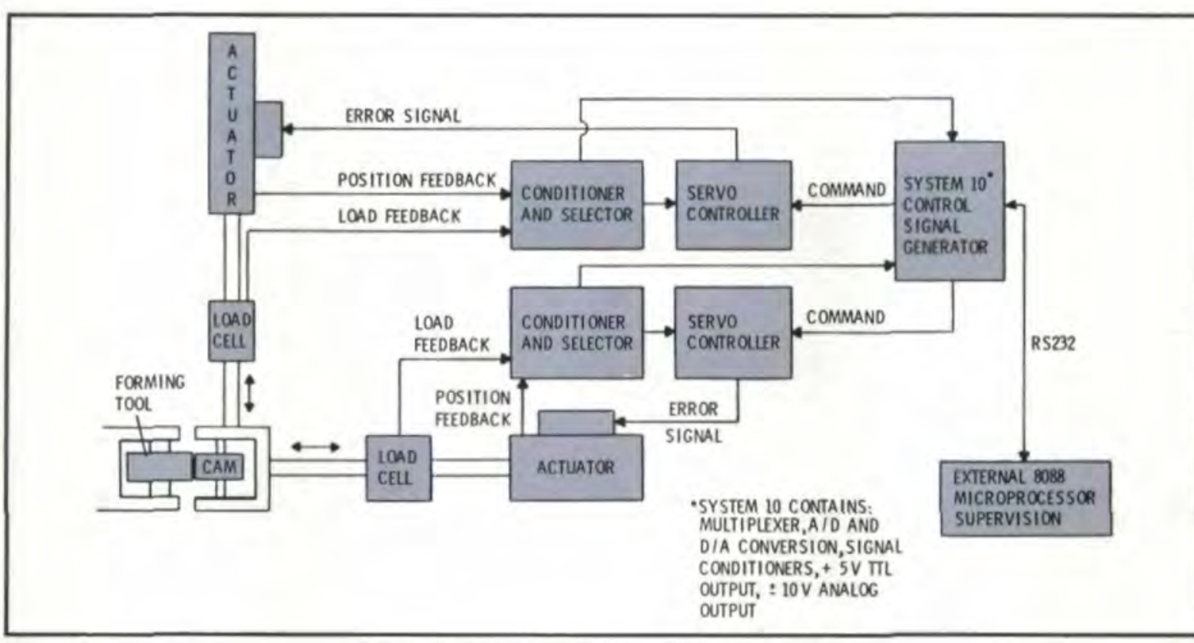

Fig. 8 – Control system for interactive gear forming.

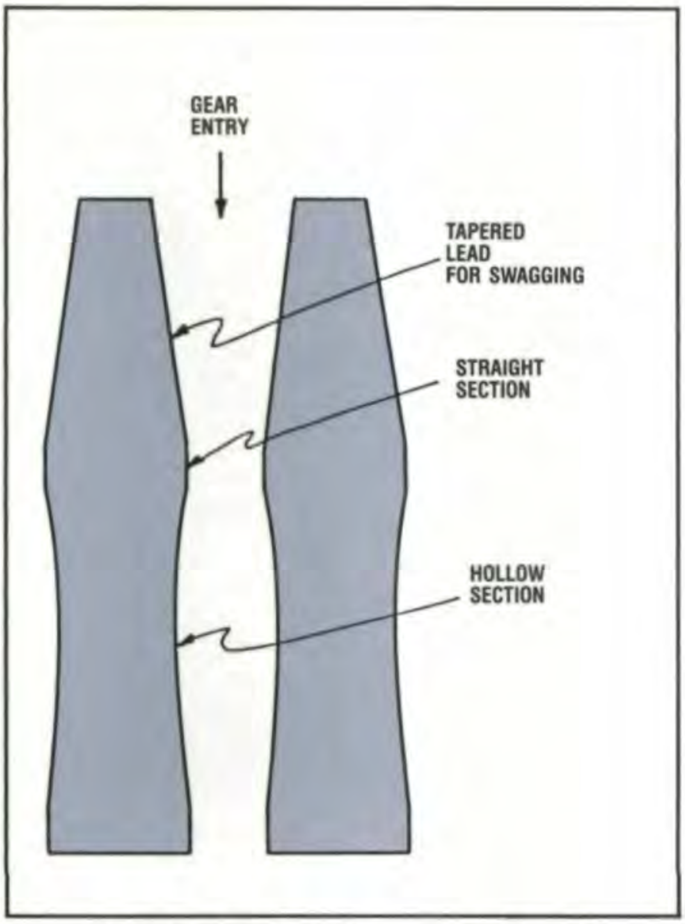

Fig. 9 – Special lead design for swagging and crowning.

tooth profile. A 0-10 volt analog output is used as a control input for real time process control.

Preliminary results on the finishing of gears by rolling in the metastable austenitic condition have indicated a potential for substantial improvements in gear accuracy. Processing has been performed on a hobbed gear with an initial gear quality of approximately AGMA 8. The microstructural examination of the finished gear indicated that approximately ½ to ¾ mil of material was severely worked by the treatment. Considerable improvements in surface finish have also resulted. An average starting surface roughness of 43.2 microinches CLA has been transformed to an average roughness of 11.7 microinches after processing. The retained austenite at the surface of an ausformed gear is about 7%, which is similar to that achieved by conventional finishing that includes both cryogenic treatment and shot peening. The hardness profile of the surface ausformed gear tooth was identical to the conventionally treated gear below the depth of ausforming.

The initial experiments provided great insight into the potential economic advantages of thermomechanical finishing. The ausforming gear rolling operation takes 51 seconds to complete, during which time a crown contour can also be developed on each tooth. This compares to approximately 38 minutes of grinding time to finish this same gear without the crown. If crown grinding were performed, the finishing time would be closer to one hour. Since significant deformation can be achieved by thermomechanical working, additional cost savings can be realized by the elimination of shaving operations or by requiring less dimensional control during rough cutting or hobbing operations. In the case of gear finishing by rolling, a significant cost savings may be realized in the inspection phase by eliminating the need for match setting of gears.

Conclusion

Low temperature thermomechanical processing has considerable potential for the finishing of precision machine elements to net shape. The feasibility of applying ausforming, one such process, to the finishing of spur gears has already been demonstrated. In this process, the final dimensions and finish quality are achieved by thermomechanically working the carburized cases of gear teeth while they are still in the metastable austenitic condition prior to quenching to martensite. The results of such processing methods are (1) the elimination of several manufacturing steps including grinding and hard finishing, (2) the generation and retention of surface compressive residual stresses, and (3) the achievement of ausform strengthening in the surface layers subjected to the high operating stresses. The following benefits are derived from these effects: significantly lower manufacturing costs, greater yield strength, improved fracture resistance, greater pitting and bending fatigue strength and greater product reliability.

The encouraging results from previous studies justify additional research and development to refine and implement the technology and to extend it to the other machine elements such as bearings, splines, cams, rollers, clutch surfaces and shafts.

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Acknowledgement:
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